

Stimulation of Hepatocyte Glucose Metabolism by Novel Small Molecule Glucokinase Activators

Katy J. Brocklehurst,¹ Victoria A. Payne,² Rick A. Davies,¹ Debra Carroll,¹ Helen L. Vertigan,¹ Heather J. Wightman,¹ Susan Aiston,² Ian D. Waddell,¹ Brendan Leighton,¹ Matthew P. Coghlan,¹ and Lorraine Agius²

Glucokinase (GK) has a major role in the control of blood glucose homeostasis and is a strong potential target for the pharmacological treatment of type 2 diabetes. We report here the mechanism of action of two novel and potent direct activators of GK: 6-[(3-isobutoxy-5-isopropoxybenzoyl)amino]nicotinic acid (GKA1) and 5-[(3-isopropoxy-5-[2-(3-thienyl)ethoxy]benzoyl)amino]-1,3,4-thiadiazole-2-carboxylic acid (GKA2), which increase the affinity of GK for glucose by 4- and 11-fold, respectively. GKA1 increased the affinity of GK for the competitive inhibitor mannoheptulose but did not affect the affinity for the inhibitors palmitoyl-CoA and the endogenous 68-kDa regulator (GK regulatory protein [GKRP]), which bind to allosteric sites or to *N*-acetylglucosamine, which binds to the catalytic site. In hepatocytes, GKA1 and GKA2 stimulated glucose phosphorylation, glycolysis, and glycogen synthesis to a similar extent as sorbitol, a precursor of fructose 1-phosphate, which indirectly activates GK through promoting its dissociation from GKRP. Consistent with their effects on isolated GK, these compounds also increased the affinity of hepatocyte metabolism for glucose. GKA1 and GKA2 caused translocation of GK from the nucleus to the cytoplasm. This effect was additive with the effect of sorbitol and is best explained by a "glucose-like" effect of the GK activators in translocating GK to the cytoplasm. In conclusion, GK activators are potential antihyperglycemic agents for the treatment of type 2 diabetes through the stimulation of hepatic glucose metabolism by a mechanism independent of GKRP. *Diabetes* 53:535–541, 2004

From the ¹Cardiovascular and Gastrointestinal Department, AstraZeneca, Macclesfield, Cheshire, U.K.; and the ²Department of Diabetes, School of Clinical Medical Sciences, University of Newcastle upon Tyne, Newcastle upon Tyne, U.K.

Address correspondence and reprint requests to Dr. Lorraine Agius, University of Newcastle, Department of Diabetes, Medical School, Framlington Place, Newcastle upon Tyne, NE2 4HH, U.K. E-mail: loranne.agius@ncl.ac.uk.

Received for publication 7 October 2003 and accepted in revised form 11 December 2003.

I.D.W. holds stock in GlaxoSmithKline and Pfizer. M.P.C. holds stock in GlaxoSmithKline.

Fluorescein isothiocyanate; GK, glucokinase; GKA1, 6-[(3-isobutoxy-5-isopropoxybenzoyl)amino]nicotinic acid; GKA2, 5-[(3-isopropoxy-5-[2-(3-thienyl)ethoxy]benzoyl)amino]-1,3,4-thiadiazole-2-carboxylic acid; GKRP, GK regulatory protein; MEM, minimum essential medium.

© 2004 by the American Diabetes Association.

Type 2 diabetes is a complex disease caused by defects in both the action and secretion of insulin, leading to fasting hyperglycemia and vascular complications. Current therapies do not achieve adequate control of glycemia in type 2 diabetes, and there is a growing need for novel drugs with improved efficacy to treat this disease (1).

The liver maintains glucose homeostasis in the nondiabetic state by net uptake of postprandial glucose when blood glucose exceeds the euglycemic threshold and by net production of glucose in the postabsorptive state and during fasting to maintain euglycemia. Hyperglycemia in type 2 diabetes is in part due to an altered hepatic glycemic threshold demonstrated by the lack of suppression of hepatic glucose production in the absorptive state and by excessive glucose production in the postabsorptive state (2). Enzymes that have a high control strength on hepatic glucose metabolism are potential targets for controlling hepatic glucose balance and thereby blood glucose levels in type 2 diabetes. One strong candidate in this respect is glucokinase (GK) (hexokinase IV or D), which catalyzes the first step in hepatic glucose metabolism and has a very high control strength on hepatic glucose metabolism (3). This isoform of hexokinase is expressed in pancreatic β -cells, where it is a critical component of the glucose sensory mechanism for regulation of insulin secretion (4), and in neuroendocrine cells, where it may act as a glucose sensor (5). GK differs in its kinetic properties from the other hexokinase isoforms in having a low affinity for glucose and sigmoidal kinetics, which accounts for its role as a glucose sensor (4,6).

The importance of GK in control of blood glucose homeostasis in humans is evident from the impact of mutations in the GK gene. Heterozygous loss-of-function mutations in the GK gene cause maturity-onset diabetes of the young, type 2 (7). Conversely, activating mutations cause hyperinsulinemia and hypoglycemia (8,9). Studies in rodents also support a critical role for GK in glucose homeostasis. Mice that are homozygous for disruption of the GK gene die from diabetes within days of birth, whereas the heterozygotes are hyperglycemic (10,11). Liver-specific GK overexpression in nondiabetic mice improved glucose tolerance (12,13), and in high-fat diet-induced diabetic mice, adenoviral overexpression of GK improved glucose tolerance and decreased fasting blood

glucose with concomitant decreased insulin secretion (14).

In the liver, GK activity is regulated by hormonal control of gene expression (15) and by a 68-kDa GK regulatory protein (GKRP), which inhibits GK competitively with respect to glucose (16). The binding affinity of GKRP for GK is increased by fructose 6-phosphate and decreased by fructose 1-phosphate, which binds to the same site on GKRP (17). GKRP also determines the subcellular location of GK and sequesters the enzyme in the nucleus in the fasted state (18). This mechanism enables rapid translocation of the enzyme to the cytoplasm in response to a rise in the extracellular concentration of glucose or fructose that occurs after a meal, resulting in a rapid increase in the rate of glucose phosphorylation (19). The role of this mechanism in regulating glucose metabolism is evident from the correlation between the rate of glucose phosphorylation and the free GK activity that is not bound to GKRP (19–21) and from the stimulation of glucose disposal by fructose administration in vivo (22–24). Accordingly, it can be hypothesized that agents that cause either direct activation of GK or its dissociation from GKRP (25) are a potential strategy for stimulating hepatic glucose disposal in hyperglycemic conditions.

We and others (25) have attempted to identify low-molecular weight activators of GK that may offer a novel therapeutic strategy for type 2 diabetes. A screening approach was used and compounds were selected based on activation of human GK and modulation of glucose metabolism in primary rat hepatocytes. In this study, we report the mechanism of action of two compounds, with distinct chemical structures, on GK activity and glucose metabolism in hepatocytes.

RESEARCH DESIGN AND METHODS

Expression and purification of recombinant GK and GKRP. All recombinant proteins described were cloned from rat or human cDNA using PCR. Human liver, human pancreatic, and rat liver GKs were expressed in *E. coli* with an NH₂-terminal 6His tag and purified using Ni-NTA chromatography. The protein was dialyzed in buffer A (25 mmol/l HEPES, pH 7.3, 150 mmol/l KCl, 1 mmol/l MgCl₂, 1 mmol/l DTT, and 5 mmol/l glucose) containing 50% glycerol and stored at –80°C. Human GKRP was expressed in *E. coli* with a COOH-terminal FLAG tag, purified by DEAE sepharose followed by M2 anti-FLAG agarose, and dialyzed in buffer A containing 20% glycerol and stored at –80°C. Recombinant proteins were >95% pure, as assessed by SDS/PAGE analysis.

Enzyme activity. GK activity was measured spectrophotometrically (340 nm, room temperature, Multiskan Ascent) in an assay mixture containing 25 mmol/l KCl, 25 mmol/l Hepes pH 7.1, 5 mmol/l β-mercaptoethanol, 1 mmol/l NADP, 1 mmol/l ATP, 2.5 mmol/l MgCl₂, 2 units/ml glucose 6-phosphate dehydrogenase, 60 nmol/l GK, and the glucose concentrations indicated. In assays containing GKRP, 200 μmol/l fructose 6-phosphate was also included. GK activity with fructose as substrate was determined as reported in Agius et al. (3) but with added phosphoglucose isomerase (10 μg/ml). For assays containing both fructose and glucose, the phosphorylation of the latter was determined radiochemically using [U-¹⁴C]glucose, as previously described (26). The phosphorylation of fructose was determined by subtraction of the rate of glucose phosphorylation determined radiochemically from the rate of hexose phosphorylation determined spectrophotometrically.

Hepatocyte isolation and culture. Hepatocytes were isolated by collagenase perfusion of the liver (21) of fed male Wistar rats (180–240 g body wt). They were suspended in minimum essential medium (MEM) supplemented with 7% (vol/vol) calf serum and plated in multiwell plates for metabolic studies or on gelatin-coated coverslips for immunostaining. After cell attachment (~4 h), they were cultured in serum-free MEM containing 10 nmol/l dexamethasone. Metabolic studies were performed after 16–20 h of culture. **Metabolic studies.** Hepatocyte monolayers were incubated for 3 h in MEM with the concentrations of glucose and additions indicated. GK activators

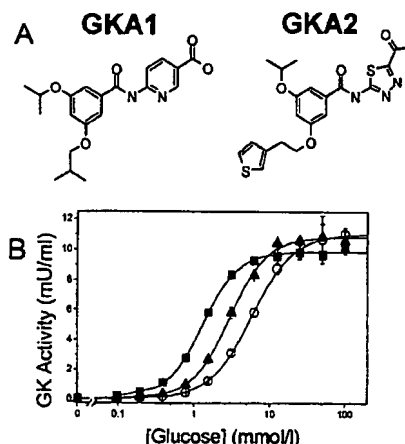


FIG. 1. GK activators increase the affinity of human GK for glucose. **A:** Chemical structures of GKA1 and GKA2. **B:** Activity of human liver GK at varying glucose concentration in the absence (○) or presence of 1 μmol/l GKA1 (▲) or 1 μmol/l GKA2 (■). A representative experiment of three summarized in Table 1.

were dissolved in DMSO, which was present at a final concentration of 0.2% (vol/vol). For determination of glucose phosphorylation or glycogen synthesis, the medium contained either [2-³H]glucose (0.5 mCi/ml) or [U-¹⁴C]glucose (1.5 mCi/ml), respectively (21). Glucose phosphorylation was determined from the formation of ³H₂O and glycolysis from the formation of lactate determined enzymatically. Glycogen synthesis from [U-¹⁴C]glucose was determined by ethanol precipitation (3). Free and bound GKs were determined by the digitonin release assay and free activity expressed as percentage of total activity (3). Rates of glucose metabolism were expressed as nanomoles of glucose metabolized in 3 h per milligram protein.

Size exclusion chromatography. Equimolar quantities (0.2 nmol in 50 μl) of 6His-pancreatic GK and GKRP-FLAG were incubated at room temperature for 30 min in buffer B (25 mmol/l Hepes, pH 7.3, 1 mmol/l EDTA, 1 mmol/l MgCl₂, 50 mmol/l KCl, 10 μmol/l fructose 6-phosphate, and 4 μmol/l recombinant proteins). The mixture was loaded onto a 2.4 ml Superdex200 column on a Pharmacia SMART system. The column was eluted (50 μl/min; 3 ml/60 min) with buffer B containing the indicated concentrations of fructose 1-phosphate and/or GK activator. Free GK, free GKRP, and the heterodimeric GK-GKRP complex were monitored from the absorbance peaks at 280 nm.

Immunostaining and imaging. Hepatocyte monolayers were washed in PBS and fixed in 4% paraformaldehyde in PBS (27). They were stained for GK with a rabbit IgG against human GK: 318-405 (H88, sc-7908; Santa Cruz) and FITC-labeled anti-rabbit IgG (27). Imaging for fluorescein isothiocyanate (FITC) fluorescence was performed using a Nikon Eclipse E400 epifluorescence microscope with a narrow-band filter (B-2EC). Three representative fields were selected for each condition comprising between 40 and 60 nuclei. For image capture, the maximum nuclear intensity of the control incubations was set at ~240 mean pixel intensity by adjustment of the exposure time and gain. All treatments within an experiment were captured using the settings selected for the controls. The mean pixel intensity of the nuclear and cytoplasmic areas was analyzed from the gray images using Lucia G/F analysis software. For each incubation condition, the mean value for the nuclei and the cytoplasm was determined and the results expressed as a nuclear/cytoplasmic ratio. The expression of results as a ratio corrects for drifts in intraexperimental fluorescence intensity.

RESULTS

Identification of potent activators of recombinant GK. Human GK and GKRP were used in a spectrophotometric assay adapted for a high-throughput screen to identify compounds that activate GK either directly or by causing its dissociation from GKRP. Chemical optimization of hits identified in this screening campaign generated compounds 6-[(3-isobutoxy-5-isopropoxybenzoyl)amino]nicotinic acid (GKA1) and 5-[(3-isopropoxy-5-[2-(3-thienyl)ethoxy]benzoyl)amino]-1,3,4-thiadiazole-2-carboxylic acid (GKA2) (Fig. 1A) for further study (28,29). GKA1 and GKA2

TABLE 1
Effects of GK activators on the affinity of GK for glucose

	$S_{0.5}$ glucose (mmol/l)	Hill coefficient	V_{max} (mU/ml)
Control	5.7 ± 0.08	1.6 ± 0.03	12.3 ± 0.45
GKA1			
1 μ mol/l	$2.7 \pm 0.11^*$	$1.8 \pm 0.02^\dagger$	12.2 ± 0.75
10 μ mol/l	$1.4 \pm 0.08^*$	$2.0 \pm 0.03^\dagger$	12.4 ± 0.58
GKA2			
1 μ mol/l	$1.4 \pm 0.04^*$	$1.8 \pm 0.04^\dagger$	10.8 ± 0.52
10 μ mol/l	$0.5 \pm 0.02^*$	1.6 ± 0.03	10.3 ± 0.78

Data are means \pm SE for three experiments. * $P < 0.001$, $^\dagger P < 0.01$ vs. control.

increased the affinity of GK for glucose (Fig. 1B) by 2- and 4-fold, respectively, at 1 μ mol/l and by 4- and 11-fold, respectively, at 10 μ mol/l. There was negligible effect on V_{max} and a small increase in the Hill coefficient at 1 μ mol/l (Table 1). When the effect of GKA1 on the affinity for ATP was determined at the corresponding $S_{0.5}$ for glucose, the K_m for ATP was decreased (control = 0.26 ± 0.007 mmol/l, 1 μ mol/l GKA1 = 0.14 ± 0.003 mmol/l, 10 μ mol/l GKA1 = 0.13 ± 0.006 mmol/l), indicating that GKA1 increases the affinity for both glucose and ATP. The potency of the compounds for activation of GK was similar when rat liver, human liver, and human β -cell GKs were compared and GKA2 was three- to fourfold more potent than GKA1 (EC₅₀ at 6 mmol/l glucose, GKA1: 1.5 ± 0.3 , 1.0 ± 0.1 , and 1.2 ± 0.2 ; GKA2: 0.4 ± 0.1 , 0.3 ± 0.03 , and 0.3 ± 0.01 μ mol/l [means \pm SE] for rat liver, human liver, and human β -cell GKs, respectively).

GK can phosphorylate various hexoses, including fructose (6). The affinity of GK for fructose is increased by low concentrations (1–4 mmol/l) of glucose (30,31). This is attributed to the effect of glucose in favoring the closed conformation (31). In this study, we confirmed that glucose (1 mmol/l) increases the affinity of GK (decrease in $S_{0.5}$) for fructose. In addition, GKA1 and GKA2 (10 μ mol/l) mimicked the effect of low glucose concentration (fructose $S_{0.5}$: control, 558 ± 88 mmol/l; plus 1 mmol/l glucose, 306 ± 48 mmol/l; plus GKA1, 161 ± 15 mmol/l; plus GKA2, 143 ± 18 mmol/l [$n = 3$]). The Hill coefficient was unchanged by glucose (1 mmol/l) and the activators (control, 1.7 ± 0.2 ; glucose, 1.6 ± 0.1 ; GKA1, 1.7 ± 0.4 ; GKA2, 1.9 ± 0.3).

Effects of GKA1 on the affinity of GK for competitive inhibitors. *N*-acetylglucosamine, mannoheptulose, palmitoyl-CoA, and GKRP inhibit GK activity competitively with respect to glucose (6). *N*-acetylglucosamine and mannoheptulose are glucose analogs that are thought to bind to the catalytic site of the open and closed conformations of GK, respectively (31,32), whereas palmitoyl-CoA and GKRP bind to distinct allosteric sites. To investigate the mechanism of action of GKA1, we tested its effects on the affinity of GK for these competitive inhibitors at the corresponding $S_{0.5}$ for glucose. Activities were expressed as a percentage of controls without inhibitor (Fig. 2). GKA1 increased the affinity of GK for mannoheptulose (Fig. 2B) but did not affect the affinity for *N*-acetylglucosamine (Fig. 2A), palmitoyl-CoA (Fig. 2C), or GKRP (Fig. 2D). The lack of effect on the affinity for GKRP is unlikely to be an artifact of our assay conditions involving

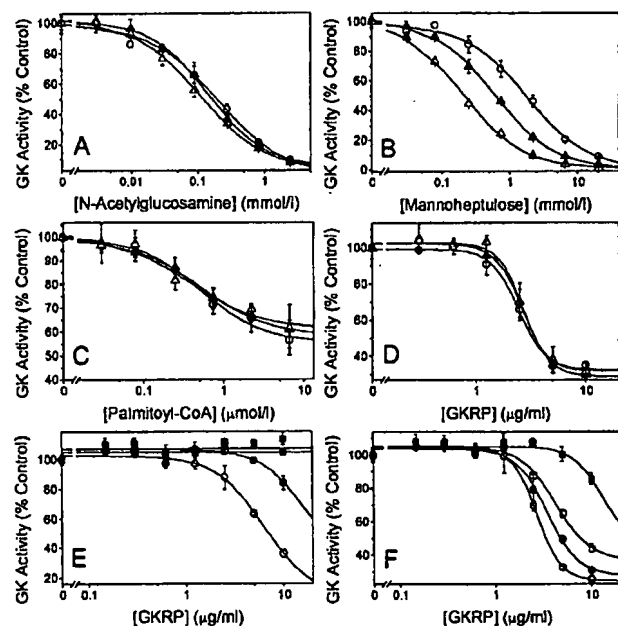


FIG. 2. GKA1 increases the affinity of GK for mannoheptulose. The affinity of GK (60 nmol/l) for *N*-acetylglucosamine (A), mannoheptulose (B), palmitoyl-CoA (C), and GKRP in the presence of 200 μ mol/l fructose 6-phosphate (D) was determined in the absence (\circ) or presence of 1 μ mol/l GKA1 (Δ) and 10 μ mol/l GKA1 (∇) at the glucose concentration corresponding to the $S_{0.5}$. E and F: Effects of 10 μ mol/l (\bullet), 100 μ mol/l (\square), and 1 mmol/l (\blacksquare) fructose 1-phosphate on the affinity for GKRP in the absence (E) or presence (F) of 200 μ mol/l fructose 6-phosphate. The data are from a representative experiment (\pm SE) performed in triplicate.

60 nmol/l GK because fructose 1-phosphate decreased the affinity for GKRP in both the absence and presence of fructose 6-phosphate (Fig. 2E and F).

To further test the effects of GKA1 on the affinity of GKRP for GK, we used size-exclusion chromatography to separate free GK and GKRP from the heterodimeric complex. We confirmed that fructose 1-phosphate causes a concentration-dependent dissociation of the complex (Fig. 3A), as previously reported by Vandercammen and Van Schaftingen (33). However, GKA1 (10 μ mol/l) did not cause dissociation of the complex (results not shown). Furthermore, when the effects of GKA1 (10 μ mol/l) were tested in the presence of 10 μ mol/l fructose 1-phosphate, there was also no dissociation of the complex compared with control (10 μ mol/l fructose 1-phosphate), indicating that GKA1 did not potentiate dissociation of the complex in the presence of a submaximal concentration of fructose 1-phosphate (Fig. 3B). Likewise, a high glucose concentration (35 mmol/l) also did not cause dissociation of the complex (results not shown). Together, these results show that GKA1, like glucose and unlike fructose 1-phosphate, does not cause dissociation of the GK-GKRP complex and it also does not affect the inhibition of GK by GKRP.

Stimulation of glucose metabolism in hepatocytes by GKA1 and GKA2. The only known physiological activators of GK in liver are precursors of fructose 1-phosphate (fructose and sorbitol), which causes dissociation of GK from GKRP (20,34). To test the efficacy of GKA1 and GKA2 at stimulating glucose metabolism in hepatocytes, we compared their effects with sorbitol, which is taken up by

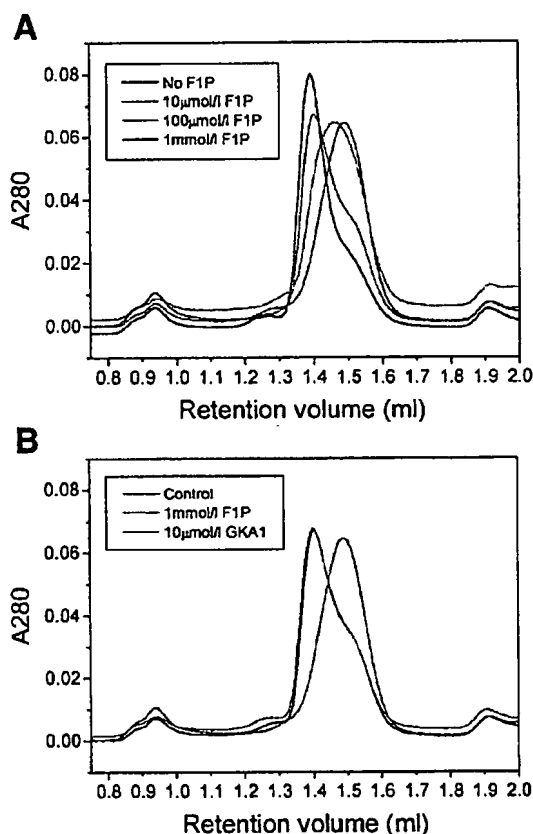


FIG. 3. GKA1 does not cause dissociation of the GKRK-GK complex. Analytical size exclusion of GK and GKRK showing separation of the individual proteins from the complex in the presence of 10 $\mu\text{mol/l}$ fructose 1-phosphate. A: Dissociation of the complex by increasing concentrations of fructose 1-phosphate (F1P). B: Dissociation of the complex by 1 mmol/l fructose 1-phosphate but not by 10 $\mu\text{mol/l}$ GKA1 plus 10 $\mu\text{mol/l}$ fructose 1-phosphate relative to control containing 10 $\mu\text{mol/l}$ fructose 1-phosphate.

hepatocytes more rapidly than fructose and is thereby more effective at stimulating glucose metabolism (20,34). As expected, sorbitol caused a concentration-dependent increase in free GK, glucose phosphorylation, glycolysis, and glycogen synthesis (Fig. 4), with half-maximal effect at ~ 20 – 30 $\mu\text{mol/l}$. GKA1 and GKA2 caused a similar increase in free GK as that achieved by maximally effective concentrations of sorbitol, and they stimulated glucose phosphorylation, glycolysis, and glycogen synthesis at all concentrations tested above 1 $\mu\text{mol/l}$, with half-maximal effect at 2–3 $\mu\text{mol/l}$ for GKA1 and 1 $\mu\text{mol/l}$ for GKA2. Although GKA1 and GKA2 caused a stimulation of glycogen synthesis that was similar to that caused by sorbitol, they caused a greater stimulation of glucose phosphorylation (Fig. 4).

GKA1 and GKA2 stimulate translocation of GK from the nucleus to the cytoplasm. To further investigate the dissociation of bound GK by GKA1 and GKA2 in hepatocytes (Fig. 4A), we tested the combined effects of the GK activators and sorbitol on dissociation of bound GK and on translocation of GK from the nucleus by immunofluorescence staining (Fig. 5). GKA1 and GKA2 had additive effects with sorbitol on dissociation of bound GK, similar to the additive effect of glucose and sorbitol (Fig. 5A).

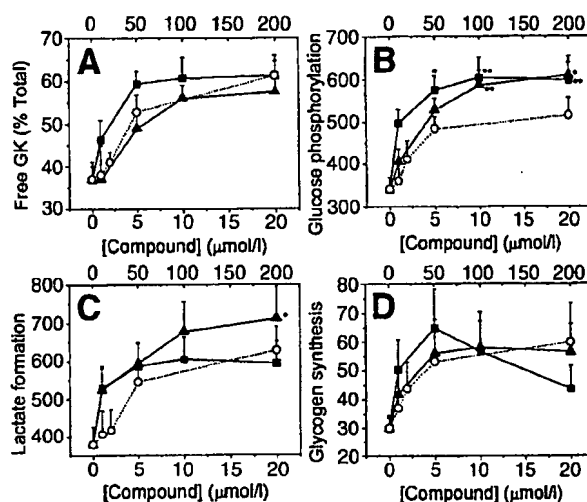


FIG. 4. Comparison of the effects of the GK activators and sorbitol on free GK activity and glucose metabolism in hepatocytes. Hepatocyte monolayers were incubated for 3 h in MEM containing 10 mmol/l glucose and the indicated concentrations of sorbitol (○; scale on top x-axis) or GKA1 (Δ) or GKA2 (■) (scale on bottom x-axis). Free GK activity (A) determined by the digitonin release assay is expressed as percentage of total activity. Glucose phosphorylation (B), lactate formation (C), and glycogen synthesis (D) are expressed as nanomoles of glucose metabolized (B and D) or lactate formed (C) in 3 h/mg cell protein. The data are the means \pm SE for four (A), eight (B and C), and five (D) hepatocyte cultures. * $P < 0.05$, ** $P < 0.005$ vs. 200 $\mu\text{mol/l}$ sorbitol.

They caused translocation of GK from the nucleus, as shown by the decrease in the nuclear/cytoplasmic staining (Fig. 5B). This was additive to the effect of sorbitol, suggesting that they may act by a similar mechanism as glucose.

GKA1 increases the affinity of hepatocyte glucose metabolism for glucose. When the effect of GKA1 was tested at varying glucose concentrations, it stimulated GK dissociation, glucose phosphorylation, and glycogen synthesis at glucose concentrations up to 35 mmol/l (Fig. 6). However, the fractional stimulation was greater at low glucose (5–10 mmol/l) than at 35 mmol/l glucose (80–140 vs. 20% for glucose phosphorylation and three- to fivefold vs. 30% for glycogen synthesis). GKA1 decreased the glucose concentration that caused half-maximal stimulation from 21 ± 0.5 to 15 ± 1 mmol/l for glucose phosphorylation and from 23 ± 1 to 11 ± 1 mmol/l for glycogen synthesis.

DISCUSSION

The rate of glucose metabolism by hepatocytes is dependent on the level of expression of GK, on the molar ratio of GK/GKRK (21), and on the concentration of fructose 1-phosphate, which causes dissociation of GK from GKRK (19–21). Type 2 diabetes is associated with impaired glucose tolerance and incomplete suppression of hepatic glucose production by hyperglycemia. These defects can be corrected, in part, by fructose administration (23,24), supporting a role for GK as a potential therapeutic target for type 2 diabetes. As a first step toward a novel therapeutic strategy for the control of glycemia in type 2 diabetes, our aim was to identify potent activators of GK that increase the affinity of liver cells for glucose and

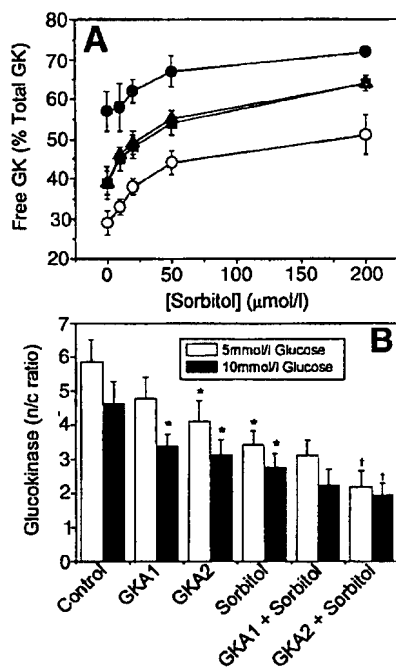


FIG. 5. GK activators have additive effects with sorbitol on GK translocation in hepatocytes. *A*: Hepatocytes were incubated for 1 h in medium containing the indicated concentrations of sorbitol in either the presence of 5 mmol/l glucose alone (○) or the additional presence of 5 μmol/l GKA1 (▲) or 1 μmol/l GKA2 (■) or in the presence of 25 mmol/l glucose (●). Free GK is expressed as a percentage of total activity. *B*: Hepatocytes were incubated for 1 h with sorbitol (200 μmol/l) and/or the GK activators (10 μmol/l) in medium with either 5 or 10 mmol/l glucose. The nuclear/cytoplasmic (n/c) ratio of GK was determined by immunofluorescence staining. The data are the means \pm SE for four to five cultures. * $P < 0.05$ vs. corresponding glucose control; † $P < 0.05$ vs. corresponding sorbitol.

thereby lower the hepatic glucose threshold. Although there are various known competitive inhibitors of GK, both physiological and pharmacological (6,16), there are as yet no clearly established physiological activators of GK other than fructose 1-phosphate, which indirectly activates GK by causing its dissociation from GKRP. We report here the structures of two chemically distinct direct activators of GK that potentially stimulate hepatic glucose metabolism with a generally similar profile as physiologi-

cal activation by precursors of fructose 1-phosphate but by a mechanism that is independent of GKRP.

GKA1 and GKA2 increase the affinity of human GK for glucose by 4- to 10-fold with an EC_{50} of 0.3–1 μmol/l. The mechanism by which GKA1 increases the affinity for glucose was investigated by testing its effects on the affinity of GK for various competitive inhibitors. GKA1 did not affect the affinity for *N*-acetylglucosamine, which binds to the catalytic site (35), or for palmitoyl-CoA and GKRP, which bind to allosteric sites (6). However, it increased the affinity for mannoheptulose, which is thought to bind to the catalytic site (31,32). This glucose analog differs from *N*-acetylglucosamine in its effects on the cooperativity of GK for glucose (36). This has been explained by binding of these inhibitors to the open (*N*-acetylglucosamine) or closed (mannoheptulose) conformations of GK (31,32). Further insight into the mechanism of action of the GK activators can be envisaged from recent studies on the kinetic properties of GK mutants. Mutations of residues in the catalytic site that interact with glucose affect the affinity for glucose, *N*-acetylglucosamine, and mannoheptulose (37–39). However, mutations of residues distant from the catalytic site affect the affinity for glucose and mannoheptulose but not *N*-acetylglucosamine (31,37). Most, though not all, of the activating mutations are in the hinge region of the bipartite structure (8,9,32,38). It is assumed that they favor the closed conformation, which has a higher affinity for glucose. The effects of GKA1 in increasing the affinity for glucose and mannoheptulose, but not *N*-acetylglucosamine, are very similar to those of activating mutations. Therefore, we propose that GKA1 binds to GK at a site distinct from both the catalytic site and the allosteric sites for palmitoyl-CoA and GKRP. Occupancy of this allosteric activation site would favor the high-affinity closed conformation. It remains speculative whether this site has a physiological ligand or binds glucose analogs.

The efficacy of a pharmacological activator of GK would be dependent on its cellular efficacy. It was crucial, therefore, to confirm that the GK activators stimulate glucose metabolism in hepatocytes. We show that GKA1 and GKA2 are potent activators (EC_{50} of 1 μmol/l for GKA2 and ~2–3 μmol/l for GKA1) of glucose metabolism in hepatocytes. The similarity in the effects of the activators

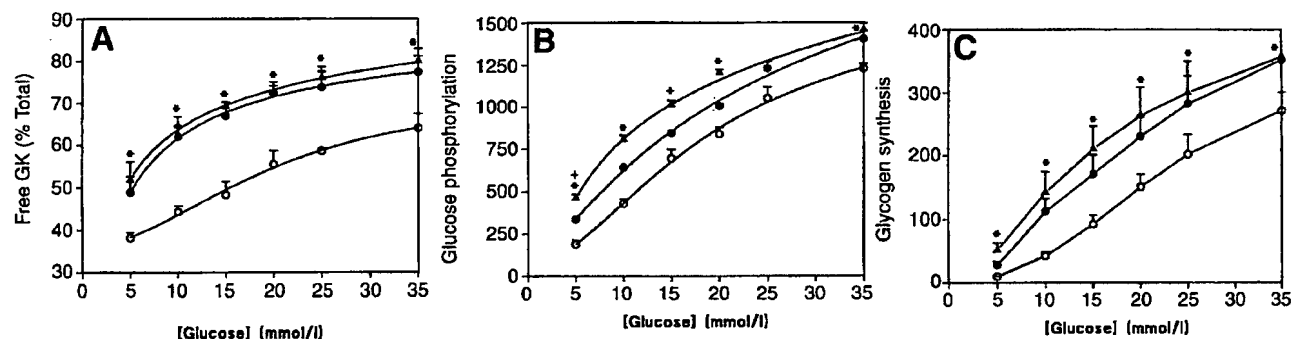


FIG. 6. Effects of GKA1 at varying glucose concentration. Hepatocytes were incubated for 3 h in medium with the glucose concentrations indicated in either the absence (○) or presence of 50 μmol/l sorbitol (●) or 10 μmol/l GKA1 (▲). Glucose phosphorylation (*B*) and glycogen synthesis (*C*) are expressed as nanomoles of glucose metabolized in 3 h per milligram cell protein. The data are the means \pm SE for four to five cultures. * $P < 0.05$, GKA1 vs. corresponding control; † $P < 0.05$, GKA1 vs. corresponding incubations with sorbitol.

and sorbitol suggests that the compounds are selective for GK and do not appear to affect downstream sites.

The stimulation of glucose metabolism by sorbitol is explained by the fructose 1-phosphate-induced dissociation of GK from GKR and its translocation to the cytoplasm (18–20). The finding that the GK activators caused dissociation of bound GK and translocation to the cytoplasm appeared incongruous with the size exclusion data showing that GKA1 does not dissociate GK from GKR. High glucose concentration and glucose analogs that are not metabolized by GK to a significant extent (5-thioglucose and mannoheptulose) also cause translocation of GK from the nucleus (18,27,36). It has been generally assumed that the translocation induced by glucose is due to dissociation of GK from GKR. However, we confirmed by size exclusion chromatography that high glucose, like GKA1 and unlike fructose 1-phosphate, does not cause dissociation of GK from GKR. We propose the following hypothesis to account for these observations. Translocation of GK from the nucleus to the cytoplasm may require two complementary mechanisms: release of GK from GKR, which is localized predominantly but not exclusively in the nucleus (18,27), and transfer to another GK receptor that is localized predominantly in the cytoplasm (3). Various GK binding proteins have been identified by the yeast two-hybrid system (40–42) or by random peptide library screening (41), which are potential candidates for the cytoplasmic receptor. The synergistic effects of glucose, as well as precursors of fructose 1-phosphate (36), on GK translocation would then be explained by the latter promoting GK release from GKR and the former promoting its binding to cytoplasmic receptors. Therefore, the action of the GK activators on translocation would be similar to the effect of glucose. Consistent with such a “glucose-like” mechanism of action, we have also shown that like glucose, GK activators increase the affinity of GK for fructose.

Despite the general similarity in the effects of the GK activators and sorbitol, the net stimulation of glucose phosphorylation by GKA1 and GKA2 was greater than that by sorbitol. This can be explained by the combined effects of the GK activators on translocation of GK and on activation of GK. Likewise, the increase in the affinity of glucose phosphorylation and glycogen synthesis in hepatocytes for glucose by GKA1 can be explained by the combined effects on translocation and activation.

A recent study by Grimsby et al. (25) reported activation of GK by RO-28-1675. In our study, we report the structures of two novel potent activators of human GK that increase the affinity for glucose. Moreover, we demonstrate the efficacy of these compounds in stimulating glucose phosphorylation, glycolysis, and glycogen synthesis in hepatocytes. Furthermore, we show that the compounds affect the affinity for mannoheptulose but not for three other GK inhibitors, including GKR, which suggests a similar mechanism of action of the compounds to activating mutations of the GK gene (8,9,32). The compounds cause translocation of GK from the nucleus despite the fact that they do not dissociate GK from GKR. We explain this by our finding that high glucose concentration does not cause dissociation of the GK-GKR complex. This supports the hypothesis for a glucose-like effect of the compounds on GK translocation.

In the nondiabetic state, the liver maintains glucose homeostasis by net uptake or net production of glucose relative to the prevailing glycemia. This mechanism is impaired in type 2 diabetes when an excessive production of glucose by the liver is a major contributor to fasting hyperglycemia. GK activators that stimulate net uptake of glucose by the liver by increasing the affinity of the liver cell for glucose would therefore shift the balance from net glucose output to net uptake and would be predicted to lower blood glucose, as has been shown by activating mutations of the GK gene in humans. GK activators may help in the development of novel treatments for type 2 diabetes. In addition, they are powerful experimental tools that may shed new insights into our understanding of control of glucose homeostasis by GK.

ACKNOWLEDGMENTS

We thank the Medical Research Council (JREI, G0100348), Diabetes U.K. (RD01/0002364), and the Wellcome Trust for equipment grant support. We also thank AstraZeneca for providing grant funding (to V.A.P., S.A., and L.A.).

REFERENCES

1. Tadayyon M, Smith SA: Insulin sensitisation in the treatment of type 2 diabetes. *Expert Opin Investig Drugs* 12:307–324, 2003
2. DeFronzo RA: Pharmacologic therapy for type 2 diabetes mellitus. *Ann Intern Med* 131:281–303, 1999
3. Agius L, Peak M, Newgard CB, Gomez-Foix AM, Guinovart JJ: Evidence for a role of glucose-induced translocation of glucokinase in the control of hepatic glycogen synthesis. *J Biol Chem* 273:30479–30486, 1996
4. Matschinsky FM: Glucokinase as glucose sensor and metabolic signal generator in pancreatic beta-cells and hepatocytes. *Diabetes* 39:647–652, 1990
5. Schuit FC, Huypens P, Heimberg H, Pipeleers DG: Glucose sensing in pancreatic beta-cells: a model for the study of other glucose-regulated cells in gut, pancreas, and hypothalamus. *Diabetes* 50:1–11, 2001
6. Cardenas ML: *Glucokinase: Its Regulation and Role in Liver Metabolism*. Austin, TX, RG Landes, 1995
7. Vionnet N, Stoffel M, Takeda J, Yasuda K, Bell GI, Zouali H, Lesage S, Velho G, Iris F, Passa P, Froguel P, Cohen D: Nonsense mutation in the glucokinase gene causes early-onset non-insulin-dependent diabetes mellitus (Letter). *Nature* 356:721–722, 1992
8. Glaser B, Kesavan P, Heyman M, Davis E, Cuesta A, Buchs A, Stanley CA, Thornton PS, Permutt MA, Matschinsky FM, Herold KC: Familial hyperinsulinism caused by an activating glucokinase mutation. *N Engl J Med* 338:226–230, 1998
9. Christesen HB, Jacobsen BB, Odili S, Buettger C, Cuesta-Munoz A, Hansen T, Brusgaard K, Massa O, Magnuson MA, Shiota C, Matschinsky FM, Barbeti F: The second activating glucokinase mutation (A456V): implications for glucose homeostasis and diabetes therapy. *Diabetes* 51:1240–1246, 2002
10. Grupe A, Hultgren B, Ryan A, Ma YH, Bauer M, Stewart TA: Transgenic knockouts reveal a critical requirement for pancreatic beta cell glucokinase in maintaining glucose homeostasis. *Cell* 83:69–78, 1995
11. Postic C, Shiota M, Niswender KD, Jetton TL, Chen Y, Moates JM, Shelton KD, Lindner J, Cherrington AD, Magnuson MA: Dual roles for glucokinase in glucose homeostasis as determined by liver and pancreatic beta cell-specific gene knock-outs using Cre recombinase. *J Biol Chem* 274:305–315, 1999
12. Ferre T, Riu E, Bosch F, Valera A: Evidence from transgenic mice that glucokinase is rate limiting for glucose utilization in the liver. *FASEB J* 10:1213–1218, 1996
13. Harilalan N, Farrelly D, Hagan D, Hillyer D, Arbeeney C, Sabrah T, Treloar A, Brown K, Kalinowski S, Mookhtiar K: Expression of human hepatic glucokinase in transgenic mice liver results in decreased glucose levels and reduced body weight. *Diabetes* 46:11–16, 1997
14. Desai UJ, Slosberg ED, Boettcher BR, Caplan SL, Fanelli B, Stephan Z, Gunther VJ, Kaleko M, Connolly S: Phenotypic correction of diabetic mice by adenovirus-mediated glucokinase expression. *Diabetes* 50:2287–2295, 2001

15. Iynedjian PB: Mammalian glucokinase and its gene. *Biochem J* 293:1-13, 1993
16. Van Schaftingen E, Detheux M, Veiga-da-Cunha M: Short-term control of glucokinase activity: role of a regulatory protein. *FASEB J* 8:414-419, 1994
17. Veiga-da-Cunha M, Van Schaftingen E: Identification of fructose 6-phosphate- and fructose 1-phosphate-binding residues in the regulatory protein of glucokinase. *J Biol Chem* 277:8466-8473, 2002
18. Brown KS, Kalinowski SS, Megill JR, Durham SK, Mookhtiar KA: Glucokinase regulatory protein may interact with glucokinase in the hepatocyte nucleus. *Diabetes* 46:179-186, 1997
19. Agius L, Peak M: Intracellular binding of glucokinase in hepatocytes and translocation by glucose, fructose and insulin. *Biochem J* 296:785-796, 1993
20. Niculescu L, Veiga-da-Cunha M, Van Schaftingen E: Investigation on the mechanism by which fructose, hexitols and other compounds regulate the translocation of glucokinase in rat hepatocytes. *Biochem J* 321:239-246, 1997
21. De la Iglesia N, Mukhtar M, Seoane I, Guinovart JJ, Agius L: The role of the regulatory protein of glucokinase in the glucose sensory mechanism of the hepatocyte. *J Biol Chem* 275:10597-10603, 2000
22. Moore MC, Cherrington AD, Mann SL, Davis SN: Acute fructose administration decreases the glycemic response to an oral glucose tolerance test in normal adults. *J Clin Endocrinol Metab* 85:4515-4519, 2000
23. Moore MC, Davis SN, Mann SL, Cherrington AD: Acute fructose administration improves oral glucose tolerance in adults with type 2 diabetes. *Diabetes Care* 24:1882-1887, 2001
24. Hawkins M, Gabrieli I, Wozniak R, Vilcu C, Shamooh H, Rossetti L: Fructose improves the ability of hyperglycemia per se to regulate glucose production in type 2 diabetes. *Diabetes* 51:606-614, 2002
25. Grimsby J, Sarabu R, Corbett WL, Haynes NE, Bizzarro FT, Coffey JW, Guertin KR, Hilliard DW, Kester RF, Mahaney PE, Marcus L, Qi L, Spence CL, Teng J, Magnuson MA, Chu CA, Dvorozniak MT, Matschinsky FM, Grippo GF: Allosteric activators of glucokinase: potential role in diabetes therapy. *Science* 301:370-373, 2003
26. Van Schaftingen E: A protein from rat liver confers to glucokinase the property of being antagonistically regulated by fructose 6-phosphate and fructose 1-phosphate. *Eur J Biochem* 179:179-184, 1989
27. Mukhtar M, Stubbs M, Agius L: Evidence for glucose and sorbitol-induced nuclear export of glucokinase regulatory protein in hepatocytes. *FEBS Lett* 462:453-498, 1999
28. Hayter BR, Currie GS, Hargreaves RB, James R, Jones CD, McKerrecher D, Allen JV, Caulkett PWR, Johnstone C, Gaskin H (inventors): Amino nicotinate derivatives as glucokinase activators. Patent no. WO 03/000267, 2003 (AstraZeneca, AB)
29. Block MH, Boyd S, Bowker SS, Caulkett PWR, Hargreaves RB, James R, Johnstone C, Jones CD, McKerrecher D (inventors): Compounds effecting glucokinase. Patent no. WO 03/015774, 2003 (AstraZeneca, AB)
30. Scruiel O, Sencer A, Malaisse WJ: Glucose-induced positive cooperativity of fructose phosphorylation by human B-cell glucokinase. *Mol Cell Biochem* 175:263-269, 1997
31. Moukil MA, Van Schaftingen E: Analysis of the cooperativity of human beta-cell glucokinase through the stimulatory effect of glucose on fructose phosphorylation. *J Biol Chem* 276:3872-3878, 2001
32. Moukil MA, Veiga-da-Cunha M, Van Schaftingen E: Study of the regulatory properties of glucokinase by site-directed mutagenesis: conversion of glucokinase to an enzyme with high affinity for glucose. *Diabetes* 49:195-201, 2000
33. Vandercammen A, Van Schaftingen E: The mechanism by which rat liver glucokinase is inhibited by the regulatory protein. *Eur J Biochem* 191:483-489, 1990
34. Agius L: Control of glucokinase translocation in rat hepatocytes by sorbitol and the cytosolic redox state. *Biochem J* 298:237-243, 1994
35. Connolly BA, Trayer IP: Reaction of rat hepatic glucokinase with substrate-related and other alkylating agents. *Eur J Biochem* 90:299-308, 1979
36. Agius L, Stubbs M: Investigation of the mechanism by which glucose analogues cause translocation of glucokinase in hepatocytes: evidence for two glucose binding sites. *Biochem J* 346:413-421, 2000
37. Xu LZ, Zhang W, Weber IT, Harrison RW, Pilakis SJ: Site-directed mutagenesis studies on the determinants of sugar specificity and cooperative behavior of human beta-cell glucokinase. *J Biol Chem* 269:27458-27465, 1994
38. Veiga-da-Cunha M, Xu LZ, Lee YH, Marotta D, Pilakis SJ, Van Schaftingen E: Effect of mutations on the sensitivity of human beta-cell glucokinase to liver regulatory protein. *Diabetologia* 39:1173-1179, 1996
39. Veiga-da-Cunha M, Courtois S, Michel A, Gosselain E, Van Schaftingen E: Amino acid conservation in animal glucokinases: identification of residues implicated in the interaction with the regulatory protein. *J Biol Chem* 271:6292-6297, 1996
40. Munoz-Alonso MJ, Guillemain G, Kassiss N, Girard J, Burnol AF, Leturque A: A novel cytosolic dual specificity phosphatase, interacting with glucokinase, increases glucose phosphorylation rate. *J Biol Chem* 275:32406-32412, 2000
41. Baltrusch S, Lenzen S, Okar DA, Lange AJ, Tiedge M: Characterization of glucokinase-binding protein epitopes by a phage-displayed peptide library: identification of 6-phosphofructo-2-kinase/fructose-2,6-bisphosphatase as a novel interaction partner. *J Biol Chem* 276:43915-43923, 2001
42. Shiraishi A, Yamada Y, Tsuura Y, Fijimoto S, Tsukiyama K, Mukai E, Toyoda Y, Miwa I, Seino Y: A novel glucokinase regulator in pancreatic beta cells: precursor of propionyl-CoA carboxylase beta subunit interacts with glucokinase and augments its activity. *J Biol Chem* 276:2325-2328, 2001